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DIRECT MEASUREMENT OF ANGULAR VELOCITY USING THE 3-2-2-2 LINEAR ACCELEROMETER CONFIGURATION

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INTRODUCTION

Historically, in the automotive safety community, there has been a constant effort to obtain the motion of the rigid parts of a dummy during a laboratory simulation of a vehicle crash. Measurement of the angular motion of the dummy has been the most difficult aspect of this endeavor. Many attempts have been made to determine both angular velocity and angular acceleration of dummy components, such as the head, through the use of multiple translational accelerometers (Mertz et al, 1967, Kane et al, 1974, Padgaonkar et al, 1975, Alem et al, 1978, Bartz and Butler, 1972, Viano et al, 1987, Becker and Williams, 1975). It has been shown, in theory, that translational accelerometers placed appropriately on a rigid body could yield angular and linear accelerations, velocities, and positions. The general procedure is to first find the angular acceleration; integration of it yields angular velocity. Once the angular velocity is obtained, then a second integration is used to find the transformation from the instrument frame to the laboratory frame. In the laboratory frame, the linear acceleration can be integrated to find the linear velocity; the linear velocity can be integrated to find the linear position. Although this has been accomplished with varying degrees of success, it is still possible to improve on the current systems.

Errors in the measurements obtained from linear acceleration transducers lead to an accumulation of error in the values of the angular velocities obtained by numerical integration. In some of the procedures used for rigid body dynamics, these errors can, in turn, lead to inaccuracies in the angular acceleration (Padgaonkar, 1975). In addition, although this error accumulation in the angular acceleration can be eliminated through specific accelerometer configurations coupled with numerical procedures (Padgaonkar, 1975), Viano et al, 1987) - the problem of numerical integration to obtain angular velocity still exists.

To address the above problem: A different analytical approach can be used. It is possible to measure angular velocity directly through algebraic manipulation of the linear accelerations. It has been shown that this is possible using three triaxial clusters, (Nusholtz et al, 1991), and the geometry of a sphere. However, it may be possible in a limited manner to measure angular velocity directly using other procedures, like the 3-2-2-2 method developed at Wayne (Padgaonkar, 1975).

For example, the 3-2-2-2 is used in this paper, to evaluate hypothetical impact motion. The 3-2-2-2 method is compared to a modified 3-2-2-2 method which uses a direct calculation of angular velocity to correct the integrated angular velocity. In addition these results are compared to the SGA procedure (Nusholtz et al, 1991).

EFFECTS OF NOISE

It is important to keep in mind that the results obtained in laboratory experiments rely on digitized transducer time-histories. Contamination results from a variety of sources, such as transverse sensitivity, cable noise, thermal noise, accelerometer misalignment and mismatching, calibration errors, accelerometer nonlinearity, and Gaussian accelerometer noise. As a result, noise of both high and low frequency can enter into the data, leading to erroneous results. In the analytical comparison that follows, an attempt is made to reproduce in a limited sense the effect of this noise on a hypothetical signal. The purpose of this exercise is to illustrate the general differences in results when angular displacement is obtained by the 3-2-2-2 method and a modification of the 3-2-2-2 method. The results are presented to illustrate the general effect of the noise described above on determination of angles by the two procedures.

ANALYTICAL COMPARISON

The 3-2-2-2 system was compared, using hypothetically/ /artificially derived motion, to the 3-2-2-2 system modified to allow the use of direct calculation of angular velocity to improve the angular displacement and the SGA procedure which calculates angular velocity directly. The 3-2-2-2 configuration consists of one triaxial and 3 biaxial accelerometer clusters. To make the comparison between the SGA and the two 3-2-2-2 procedures, four triaxial clusters were artificially computer created (Figure 1). Acceleration representing rigid body motion in all six degrees of freedom was introduced (3 translations and 3 rotations) into the 12 hypothetical accelerometers. By appropriate choice of accelerometers, the configuration shown in Figure 1 can be used by either the SGA or WSU procedures to generate rigid body motion.

Induced hypothetical rigid body motion should produce accelerations that, when processed with the two 3-2-2-2 or SGA procedures, generate the original hypothetical motion. In this regard, all three procedures are valid. However, after noise has been introduced into the exact hypothetical acceleration data - each of the procedures produces results that differ from the correct motion by different degrees. Noise was introduced into the acceleration of each of the hypothetical accelerometers in Figure 1 in the following manner: a 2% miscalibration of each accelerometer, Gaussian noise with a standard deviation of 2% of the maximum acceleration was added to each accelerometer, and a 3% cross axis noise was added to each of the accelerometers.

No attempt was made to compare the procedures in terms of linear velocity, acceleration, and position. This was because the linear acceleration is dependent on the angular motion; i.e., it is not possible to induce error in the accelerations without inducing error in angular motion. Therefore, a comparison is not applicable. The comparison is for the rotational component of the rigid body motion.

To demonstrate the differences between the three systems and to gain some insights into the difference of obtaining angular velocity directly and through integration, an artificial test signal, with noise, which represent an impact in the automobile environment are used. The greatest differences in the angular motion between the three systems are observed in the angles predicted by each procedure. Therefore, the differences in the procedures will be illustrated by the differences in the angles.

METHOD

Theoretically, the equations for the 3-2-2-2 system presented by Padgaonkar, et al, can be rewritten to obtain angular velocity directly from the acceleration.

However, there is a significant problem associated with these equations: when the deonometer gets close to zero the solution for angular velocity divergences from the true solution. Figure 3 represents the angular velocity obtained by direct calculations using hypothetical motion with a very small amount of noise. Some of the points have enough error to create a divergence from the true solution, spikes in Figure 3. Therefore, when the deonometor is small the standard integration routine is used.

RESULTS

Figures 4 and 5 show the angular velocity and angles respectively for the artificial test signal used. The rotation about the Y axis is the most significant rotation. Therefore, it will be used for the comparison. Figure 6 shows the true angular velocity as well as the 3-2-2-2 angular velocity obtained by integration and integration augmented with direct calculation. In this figure it is clear that augmentation has improved the results to some degree. However, inspection of the angles for the Y direction shows that this improvement carries over to the angle. Figure 7 shows the true Y angle, the Y angle obtained by the standard 3-2-2-2 method, the Y angled obtained by integration augmented by direct calculation and the Y angle obtained by the SGA direct calculation method. From the figure it can be seen that, in this example, augmenting the integration method can improve the response, however, it does not improve it as much as a direct calculation such as obtained by SGA.

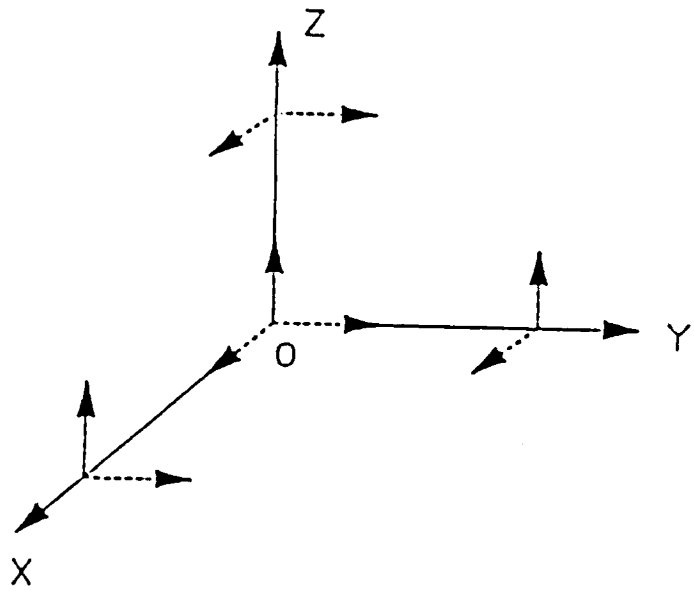

FIGURE 1

12 ACCELEROMETERS USED TO GENERATE HYPOTHETICAL MOTION

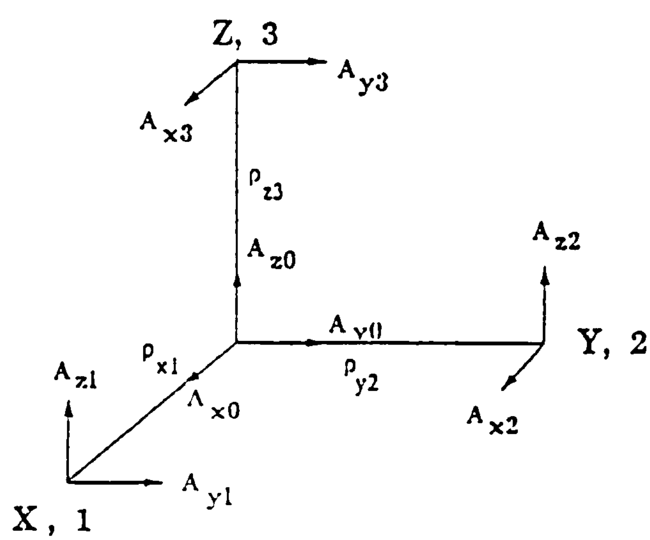

FIGURE 2

3-2-2-2 CONFIGURATION

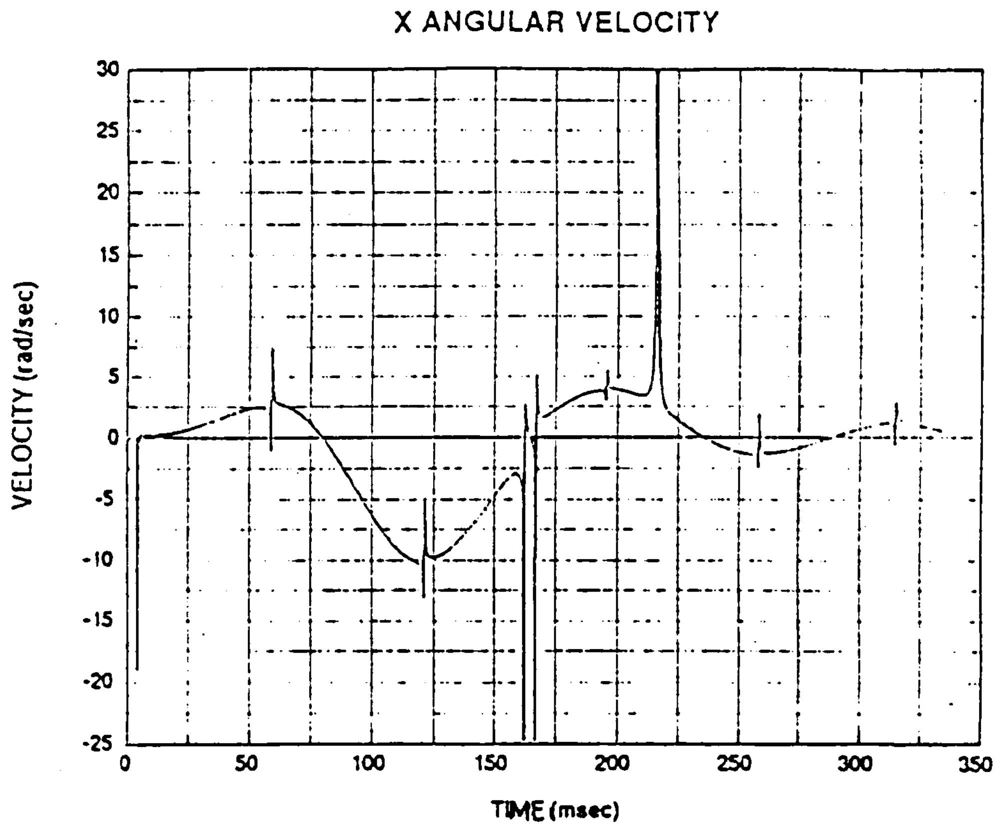

FIGURE 3

3-2-2-2 DIRECT CALCULATION OF X-ANGULAR VELOCITY

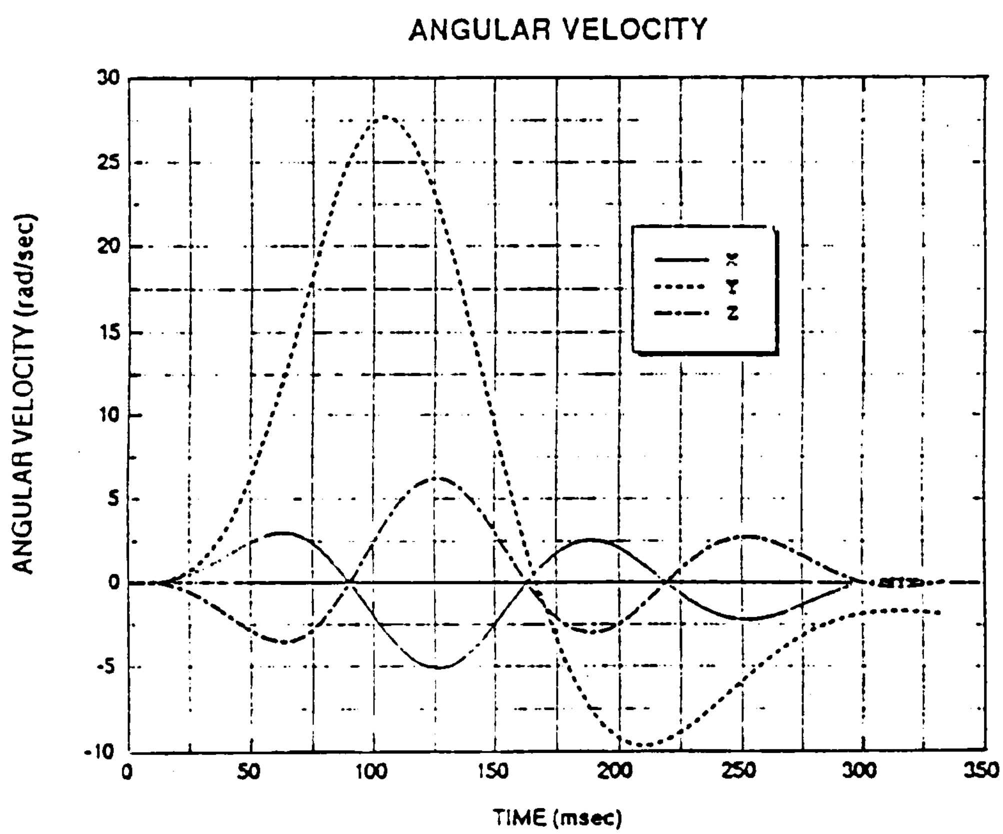

FIGURE 4

HYPOTHETICAL MOTION

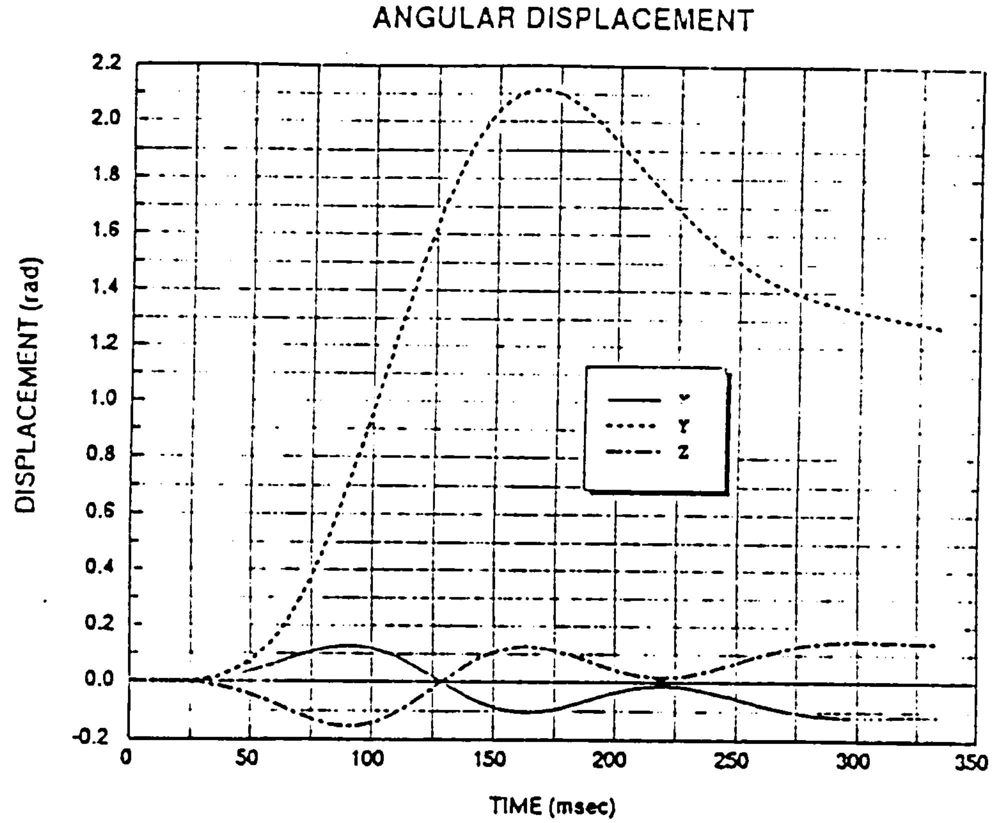

FIGURE 5

HYPOTHETICAL MOTION

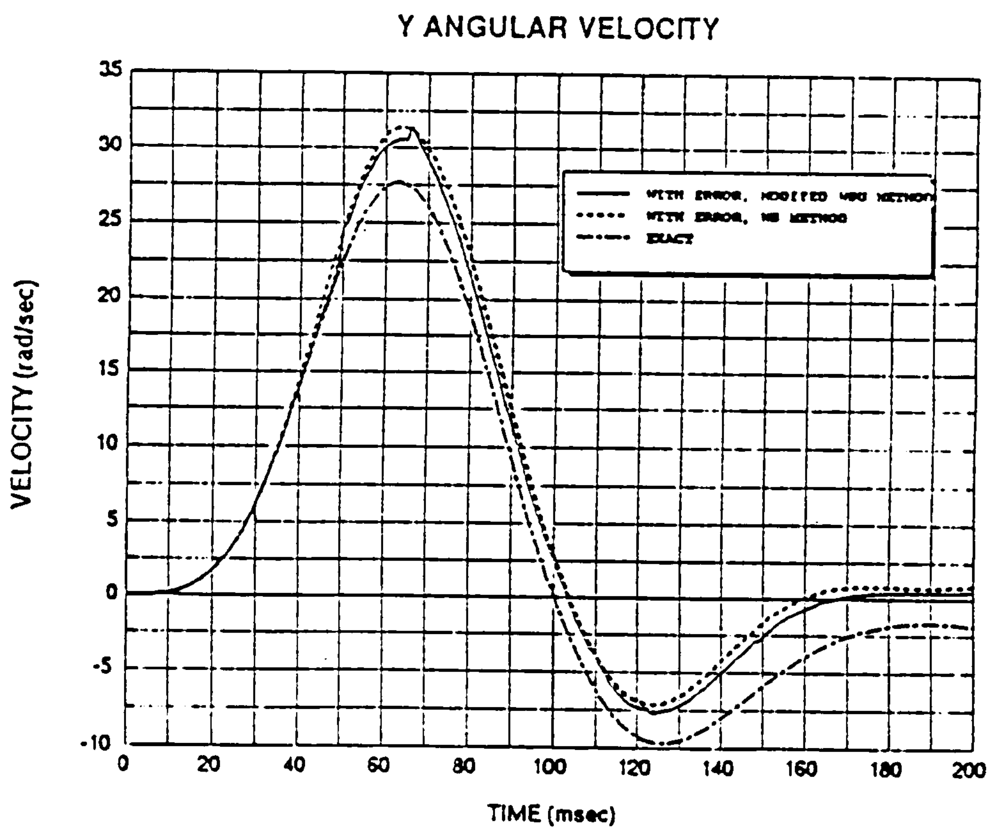

FIGURE 6

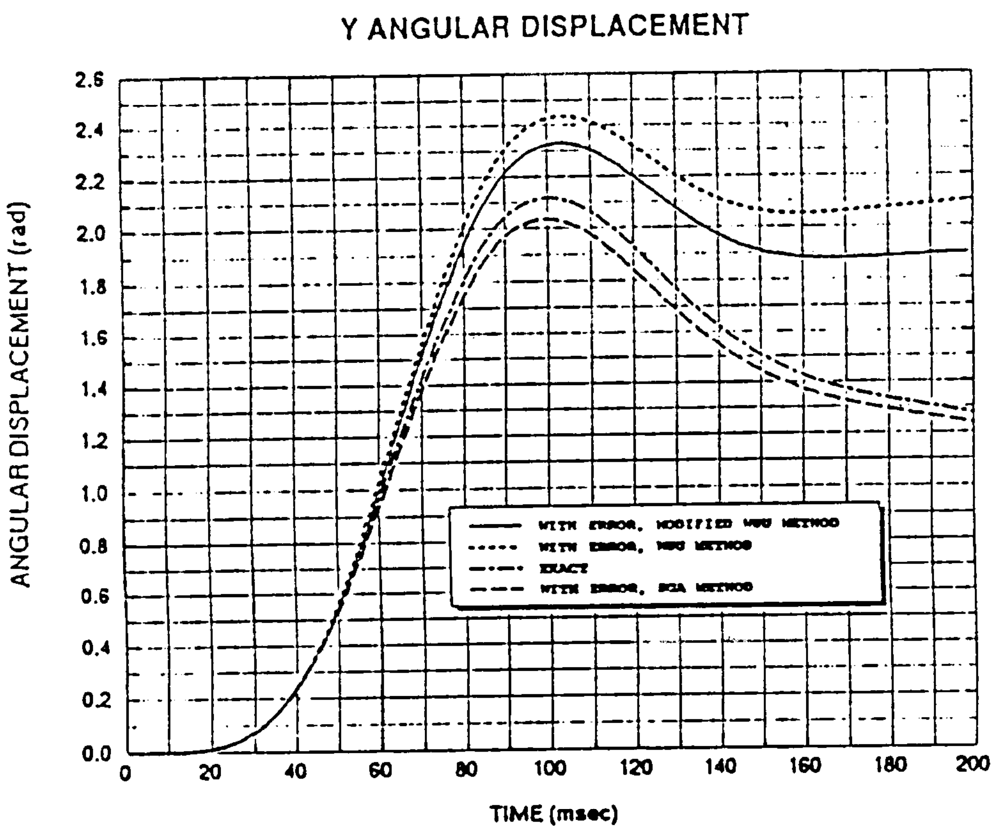
Y ANGULAR DISPLACEMENT
ANGULAR DISPLACEMENT (rad)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
160
180
200
TIME (msec)

FIGURE 7

CONCLUSION

Although the example used is a single case, a large number of artificial signals have been evaluated. In none of the test cases has the augmentation degraded the response. However, in some of the test cases there was no definable differences. Therefore, it seems that augmentation could be useful when incorporated into the 3-2-2-2 method.

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DISCUSSION

PAPER: **Direct Measurement of Angular Velocity using the 3-2-2-2 Linear Accelerometer Configuration**

SPEAKER: Guy Nusholtz, Chrysler Motors

QUESTION: Warren Hardy, Wayne State University

Earlier this year, in January and February, we were looking at approximately the same type of thing but it was more of an investigation to see what effect angular velocities cross products had in our equations under various impact situations. But what we found in examining some of our real world data specifically from GMM facial impacts, where we had a very high rate of angular acceleration or high acceleration for a very short duration, where it looks like you had a 100 to 150 milli-sec. in some of these signals that you're looking at, the angular velocities that you actually wind up with aren't necessarily all that large. Where you may have angular accelerations in thousands of radians per second squared, angular velocities may be in the order of hundreds or lower radians per sec. There's a big problem in resolving the angular velocity from these equations and there's a particular problem if there's a planer test, if you have planer rotation and if two of the axes of a nine accelerometer mount are actually in that plane, your denominator is always driven to zero and your equations are undetermined. So from a practical standpoint, it's very difficult to apply; oftentimes you will want to have two different axes in the plane, let's say if you're observing nearly planer impact, in that case it's almost always indeterminately difficult to look at. We did do, however, some longer duration testing, not on cadaver impacts but on the mount itself where it was more of a generalized motion. It wasn't planer and the axes were not oriented, say in the plane, and longer duration with lower levels of angular acceleration and higher levels of angular velocity were obtained. So in this case we were able to better determine the angular velocities from our data. It wasn't very good, but the equation was not undetermined in nearly so many cases as with the data where it's practically planar and the axes are aligned. Do you have any comments?

A: We did mimic primate impacts which are very high accelerations for very short periods of time; 2 or 3 millisec. and so you go right up and it's pretty much planer. So what we saw from those was the same type of results. You got an improvement in comparing the two different techniques; one with the correction and without the correction. It's still, whenever you have planer, that tends to be the worst case, as I understand, for any of the techniques, not just a 3-2-2-2. And so that also generates a problem. So you still have that particular problem occurring. Now once again, I didn't use real world data, I created hypothetical signals which I thought mimicked what I saw in the real world. Whether they really did or not is always open to question. And in those signals, in any of the situations we looked at, you do get an improvement. Now if the original results that you're going to get are way off, then the improvement will still be an improvement but it will also be way off.

Q: King Liu, University of Iowa

I was wondering if you ever did, for this 3-2-2-2 system, a generalized sensitivity analysis with respect to your sources of error? In the same way, for example, the way the late Prof. Hu from New Mexico did. There he shows this particular scheme or a scheme similar to this is highly prone to minute changes in alignment, and so on, thaat produce enormous changes in your output. Would you comment on that in view of what you have done?

A: We also looked at minute changes of alignment on the order of approximately 100th of a rad, which is relatively small. And when you do that you can see significant changes in the motion that you're going to get with this particular technique and with a lot of other type of techniques as well. So to answer your question, I don't know if we did a complete sensitivity study as far as that's concerned, such as alignment. We looked at different levels of noises, we looked at different parts; what happens when one accelerometer if off and all the rest are correct. Some techniques tend to be very sensitive to a particular accelerometer, depending on the motion. The others can be off by 5-10% but if this one accelerometer was off by 1%, then you end up having a large deviation from what the true motion is.

Q: How much can we trust any data generated by any of these systems using linear accelerometer schemes? If small disturbances produce large changes in your data, that says that the system is so prone to error; is any of the data worthwhile looking at?

A: That's a big question. In the case of the system that we've developed, we've looked at a large number of tests and we've compared them to film. And the assumption is that if you can predict the angles as seen by film and if you can produce the linear displacement as seen by film, then your data is accurately reproducing what's going on. What I've seen, there's a limit of time for a particular type of test in which you don't want to rely on the data. You might say, well I've tested, I've compared let's say 50 or 100 tests and in all 100 of those tests, 95-99% of them, have given me accurate results when compared to film up to 100 millisec. And then what happens is I keep using that scheme and I spot-check against film every once in a while and, unless I find a counter-indication that I can't explain, then I feel that those accelerometer techniques that we're using should be reliable. They do match film and that's only other thing that we have to check it against.

Q: I thought your direct calculation gives you angular acceleration data and then gives you angular velocity data and then ultimately, I guess, angular displacement data.

A: You have to integrate. You've got one integration step to get angular displacement.

Q: If there are such drastic changes even in the angular acceleration data, how do you end up saying that if it agrees with the film data in terms of angular displacement that your data is good?

A: What it says is that it's good in terms of angular displacement. What you're saying is it's not good necessarily in terms of angular velocity or in terms of angular acceleration. It just happened that by whatever scheme is being used, it just happens to give you the correct angular displacement.

Q: And after all, it's the angular acceleration that interests us more that the angular displacement?

A: We don't have a definitive answer...the only way I know how to do it right now is to take the hypothetical thing and we do perturb the axes by 1 or 2% and we do the type of comparison that I made, you start to develop more confidence because you know what the hypothetical data is that you put into the system and when you start rotating your accelerometers and introducing all sorts of different errors, if you get reasonably close to your angular accelerations and angular velocities, then you have a little more confidence in the system. But it's not demonstrative, not proved beyond a shadow of a doubt, we've only added some more confidence to what we're doing.